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MODIFYING DRUG-REINFORCED BEHAVIOR BY ALTERING THE ECONOMIC CONDITIONS OF THE DRUG AND A NONDRUG REINFORCER

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Six rhesus monkeys were trained to self-administer orally delivered phencyclidine (0.25 mg/mL) and saccharin (0.03% wt/vol) under concurrent fixed-ratio 16 schedules. In Condition 1 the fixed-ratio requirement for phencyclidine was changed from 16 to 4, 8, 16, 32, 64, 128 and 16 while the fixed-ratio requirement for saccharin deliveries remained constant at 16. In Condition 2 the fixed-ratio value for saccharin was systematically altered while the fixed-ratio requirement for phencyclidine remained at 16, and in Condition 3 the fixed-ratio requirements for both phencyclidine and saccharin were altered simultaneously. Water was then substituted for saccharin, and the series of fixed-ratio manipulations was replicated. The phencyclidine concentration was reduced to 0.125 mg/mL and Conditions 1 and 3 were repeated. When the fixed-ratio requirement for phencyclidine was increased and the fixed-ratio requirement for saccharin or water remained fixed at 16, phencyclidine deliveries decreased when saccharin (vs. water) was concurrently available. The magnitude of the decrease ranged from 20% to 90% (of the concurrent water condition) as the fixed-ratio requirement for phencyclidine increased from 4 to 128. When the fixed-ratio requirement for phencyclidine remained at 16 and the fixed-ratio requirements for concurrent saccharin or water varied between 4 and 128, phencyclidine deliveries decreased by 30% to 40% due to the concurrent availability of saccharin (vs. water). This decrease occurred only at the three lowest fixed-ratio values when saccharin intake was relatively high. When the fixed-ratio requirements for both phencyclidine and concurrent saccharin or water were varied simultaneously, phencyclidine deliveries were reduced from 20% to 45% when saccharin (vs. water) was concurrently present. There was little effect of reducing the phencyclidine concentration when the data were analyzed in terms of unit price (responses per milligram). Thus, changes in the fixed-ratio requirement or drug concentration were functionally similar, and unit price of phencyclidine was the variable that was influenced by the presence of concurrent saccharin. These data indicate that drug-reinforced behavior is substantially reduced when the environment is enriched with an alternative nondrug reinforcer. The economic context in which these substances are presented is an important determinant of drug-reinforced behavior.

Key words: behavioral economics, fixed-ratio schedule, oral drug self-administration, phencyclidine, reinforcer interaction, saccharin, lip-contact response, monkeys

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Nonhuman models of drug abuse have been important for identifying many factors that control the initiation and maintenance of drug abuse, such as dose, route of administration, genetic variables, and behavioral schedules (cf. Johanson & Schuster, 1981; Johanson, Woolverton, & Schuster, 1987). Most studies of the reinforcing effects of drugs have been conducted in a well-controlled laboratory environment that is intentionally devoid of other reinforcers. However, human drug-taking behavior typically occurs in an environment in which there are alternative competing reinforcers. There have been only a few laboratory studies of the effect of drug self-administration in the context of alternative nondrug reinforcers using nonhuman or human subjects.

In nonhuman studies, food intake is an alternative reinforcer that has been reliably shown to alter drug administration. Increased access to food in a food-restricted subject results in a marked reduction in drug intake (e.g., Carroll & Meisch, 1984; Nader, Grant, & Woolverton, 1989; Oei, Singer, & Jefferys, 1980); conversely, a reduction in food access in a satiated subject results in a dramatic increase in drug self-administration (e.g., Carroll & Meisch, 1984; de la Garza & Johanson, 1987; Dworkin et al., 1984). Thus, the amount of food available is an important determinant of drug-reinforced behavior. The generality of this finding has been extended across several species, routes of administration, and a wide range of drugs that are abused by humans and function as reinforcers in nonhumans (Carroll & Meisch, 1984). However, the effect is not

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due simply to a specific food and drug interaction. Similar effects have been found with sucrose (Lester & Greenberg, 1952; Samson & Falk, 1974; Samson, Roehrs, & Tolliver, 1982), glucose and saccharin (Carroll, Lac, & Nygaard, 1989), and saccharin (Carroll, 1985), a noncaloric substance. These dietary-induced changes in drug-reinforced behavior are not based on general changes in activity, liquid intake, or drug absorption (Carroll & Meisch, 1984). Instead, they may be explained by reinforcer interaction. Drug and nondrug reinforcers may be substitutable; consumption of one may increase such that demand for the other decreases (Samuelson & Nordhaus, 1985).

A few reports of studies with human subjects concur with results of nonhuman experiments. For instance, alcohol self-administration was reduced when money (Vuchinich & Tucker, 1983) or video-game playing (Landau, 1987) was available as an alternative reinforcer. Hall, Ginsberg, and Jones (1986) reported that clients were more successful at remaining abstinent from cigarette smoking if they gained weight after smoking cessation, rather than restricting food intake to maintain precessation weights. An increase in caloric intake after smoking withdrawal has been reported by others (Hatsukami, Hughes, Pickens, & Svikis, 1984). Alcohol intake was reported to decrease as subjects increased their intake of sugar and carbohydrates (Yung, Gordis, & Holt, 1983). In most of the nonhuman and human studies cited above, the magnitude and cost (response requirement) of the alternative reinforcer were not systematically varied; however, these studies strongly suggest that manipulation of alternative reinforcers may be useful for developing strategies to treat drug abuse. Response cost is an important determinant of drug self-administration (e.g., Lemaire & Meisch, 1984, 1985), tolerance (Hoffman, Branch, & Sizemore, 1987), and dependence (Carroll & Carmona, 1991).

The purpose of the present experiment was to examine the effect of response cost on behavior reinforced by concurrently available, orally delivered phencyclidine (PCP) and saccharin, a nondrug, noncaloric reinforcer. An earlier experiment showed that concurrent access to a saccharin solution (0.03% or 0.3% wt/vol) reduced self-administration of orally delivered PCP, and the magnitude of this effect decreased as PCP concentration increased (Carroll, 1985). A similar decrease in the ascending limb of the PCP concentration-response function has been produced by presenting ethanol (8% wt/vol) concurrently with PCP instead of water (cf. Carroll, 1987b), or by providing unlimited access to food (Carroll & Stotz, 1984). Thus, it appears that alternative reinforcers more effectively interfere with lower magnitudes of drug rewards than they do with higher magnitudes. In previous experiments, the cost or fixed-ratio (FR) requirement for the drug was held constant; therefore, the results may not be generalizable across a wide range of drug access conditions. In the present experiment, the FR requirements for PCP and saccharin were varied both separately and simultaneously. This further defines the optimal conditions under which an alternative reinforcer can effectively interfere with drug self-administration.

An additional goal of this experiment was to analyze the interaction between PCP and the nondrug reinforcer in behavioral economic terms. There have been a number of behavioral economic analyses comparing the same type of food at different costs, and the findings uphold economic principles (cf. Hursh, 1980; Samuelson & Nordhaus, 1985). For instance, consumer demand theory predicts that increases in price will result in decreases in consumption; however, the application of these principles to drug self-administration behavior has been very limited. The present study will determine how an alternative nondrug reinforcer alters the demand for a drug reward. Demand is defined as consumption of the drug plotted as a function of price. In economic terms, a parallel shift in the phencyclidine demand curve indicates a change in the intensity of the demand for the drug. A change in the slope of the phencyclidine demand curve indicates a change in elasticity of demand (Samuelson & Nordhaus, 1985). Elasticity is defined as performance change under increasing environmental constraints. If the slope of the demand curve is between -1 and 0, it is inelastic or more resistant to change under environmental constraint. If it is less than -1, the demand is elastic or more sensitive to environmental constraints. The concept of demand elasticity is similar to that of response strength proposed by Nevin (1974) in that behavior that is more resistant to constraints (or inelastic behavior) is "stronger." Economists use elasticity of demand to describe commodities that are important or essential to the consumer (cf. Hursh & Bauman, 1987). For example, gasoline (an essential commodity) consumption may remain relatively constant as price increases, whereas sales of theater tickets (a luxury item) may rapidly decrease as price increases.

Another economic concept that will be addressed in this experiment is unit price, which is defined in this study as the number of lip-contact responses per milligram of PCP delivered. Unit price can be changed by manipulating the response requirement (e.g., FR value) or the dose (mg/kg). A unit-price analysis of previous drug self-administration data indicates that these two variables are functionally equivalent (Bickel, DeGrandpre, Higgins, & Hughes, 1990); thus, an economic variable, unit price (response/mg), is the controlling factor. The present experiment investigated the effect of an alternative nondrug reinforcer on the functional equivalence of drug concentration and response requirement. This was accomplished by replicating the changes in response requirements with a concentration of phencyclidine that was half (0.125 mg/mL) the one initially tested (0.25 mg/mL).

METHOD

Subjects

Six adult male rhesus monkeys (*Macaca mulatta*) were used as subjects. The monkeys had previously self-administered orally delivered PCP, ethanol (M-G2), amphetamine (M-A1), etonitazene (M-B), methohexital (M-B), quinine (M-B), and saccharin (M-G2), and 2 (M-A1, M-G1) had exposure to intravenous drug self-administration procedures and a variety of drugs in another laboratory. All of the monkeys had been trained to self-administer PCP and water under concurrent FR 16 schedules during daily 3-hr sessions. Throughout this experiment, body weights were maintained at 85% of free-feeding weights by adjusting the daily food allotment. The 85% body weights during the experiment ranged from 9.3 to 12.8 kg. Weights were recorded every 2 weeks while the cages were steam cleaned. The monkeys were housed individually in their experimental chambers in a room that was controlled for temperature (24 °C) and humidity. The lights were on for 12 hr beginning at 6:00 a.m. The care and use of laboratory animals for this experiment were approved by the University of Minnesota Institutional Animal Care and Use Committee under protocol No. 9002022; the laboratory is a facility accredited by the American Association for the Accreditation of Laboratory Animal Care.

Apparatus

The monkeys were housed in custom-made stainless steel primate cages (Lab Products, Inc.). A panel was mounted on one side wall and contained two drinking devices spaced 30 cm apart; stimulus lights were located above each drinking device. A green light signaled saccharin availability and a green light that flashed 10 times per second indicated PCP availability during daily 3-hr sessions. Both lights were illuminated steady green during the 17.5-hr intersession periods when water was available from both spouts. There was a 2-hr timeout before each session and a 1.5-hr timeout after each 3-hr session during which stimulus lights were extinguished and responding had no consequences. During these times data were recorded, solutions were changed, and, during the second timeout, the monkeys were fed. The drinking devices were brass tubes 2.7 cm long and 1.2 cm in diameter. They were connected to a solenoid valve and tygon tubing that led to a 2,000-mL Nalgene reservoir mounted outside the cage. When the monkey placed its mouth on the brass spout, lip-contact responses were recorded. After the number of lip-contact responses specified by the FR schedule was completed, a solenoid valve was opened for a specified period (approximately 120 ms) and liquid was allowed to flow from the reservoirs. The liquid delivery was calibrated to be 0.55 to 0.6 mL, and was terminated if the monkey removed its mouth from the spout. The front of each cage contained a stainless steel food hopper in which the daily food allotment was placed 1 hr after the daily session. The experimental session was controlled by microcomputers (Micro Interfaces, Inc.) located in an adjacent room. Complete details of the control and recording equipment, drinking devices, and experimental chambers have been reported previously (Carroll, Santi, & Rudell, 1981; Henningfield & Meisch, 1976; Meisch & Henningfield, 1977, respectively).

Table 1

Experimental design.

Condition	Concurrent schedule			
	PCP FR	Sacc FR	PCP FR	Water FR
1	4–128[a]	16	4–128	16
2	16	4–128	16	4–128
3	4–128	4–128	4–128	4–128

[a] 4, 8, 16, 32, 64, 128.

Drug

Phencyclidine HCl was obtained from the National Institute on Drug Abuse. Saccharin was obtained from the Sigma Chemical Co. Saccharin and PCP solutions were mixed daily from stock solutions that were made weekly; they were mixed with tap water at least 20 hr before use and presented at room temperature. Concentrations are expressed in terms of the salt.

Procedure

Experimental sessions were conducted daily, 7 days per week, between 9:30 a.m. and 12:30 p.m. each day. At the start of the experiment, PCP (0.25 mg/mL) and water were available under concurrent FR 16 schedules during the daily 3-hr sessions. Subsequently, a saccharin solution (0.03% wt/vol) replaced water during the daily sessions. After behavior stabilized under the concurrent FR 16 schedules, three conditions were tested. Under Condition 1, the FR value for PCP was systematically altered according to the sequence 4, 8, 32, 16, 64, 128, 16, while the FR value for saccharin was held constant at 16. Two retests were conducted in the series at FR 16 to control for order effects. Each FR value was held constant until PCP- and saccharin-reinforced behavior became stable for at least 5 days. Stability was defined as no steadily increasing or decreasing trend over the 5-day period. Under Condition 2, the FR for PCP was held constant at 16, and the FR for saccharin was varied according to the same sequence. Under Condition 3, the FR values for both PCP and saccharin were varied according to the sequence described above (i.e., they were always equal). The three sequences of FR manipulations were made as they were for PCP and saccharin when water was concurrently available with PCP: The FR for PCP was varied, the FR for water was changed, and the FRs for both PCP and water were altered simultaneously. Side positions of PCP and saccharin were alternated every 21 days and side positions of PCP and water were alternated daily to control for possible position preferences; however, no side preferences were noted.

Table 1 summarizes the experimental design. Either PCP (0.25 mg/mL) and saccharin (0.03% wt/vol) or PCP and water were available concurrently. Each monkey was tested under each of the six conditions (as shown by the six cells in Table 1) in nonsystematic order. After this portion of the experiment was completed with the 0.25 mg/mL concentration of PCP, the PCP concentration was reduced to 0.125 mg/mL, and behavior was allowed to become stable. Conditions 1 and 3 were repeated with water or saccharin concurrently available (Table 1). The four conditions were tested in nonsystematic order across monkeys.

Most of the results are presented on arithmetic scales for clarity and to permit comparison with previous studies of orally delivered PCP and saccharin (e.g., Carroll, 1985). These data were transformed to log log scales for calculations of elasticity coefficients (i.e., slope); however, the graphs are not shown. The unit-price analysis of the functional equivalence between dose (milligrams consumed) and response requirement (FR) manipulations (Figure 9) is presented on log scales to be comparable to previous analyses (e.g., Bickel et al., 1990). Data are presented as means for the 6 monkeys because the means were representative of individual data. There were five different data sets: Conditions 1, 2, and 3 with 0.25 mg/mL PCP, comparison Conditions 1 and 3 with 0.125 mg/mL PCP, and a unit-price comparison of the 0.25 and 0.125 mg/mL PCP concentrations. To illustrate individual behavior patterns of 5 different monkeys, individual data are presented for these five data sets and are represented graphically as inserts in the larger graphs of mean data. Individual monkeys were selected based on PCP and saccharin deliveries that were similar to the mean for the group.

RESULTS

Figure 1 shows the number of liquid deliveries as a function of FR value for the conditions in which the FR for PCP was changed

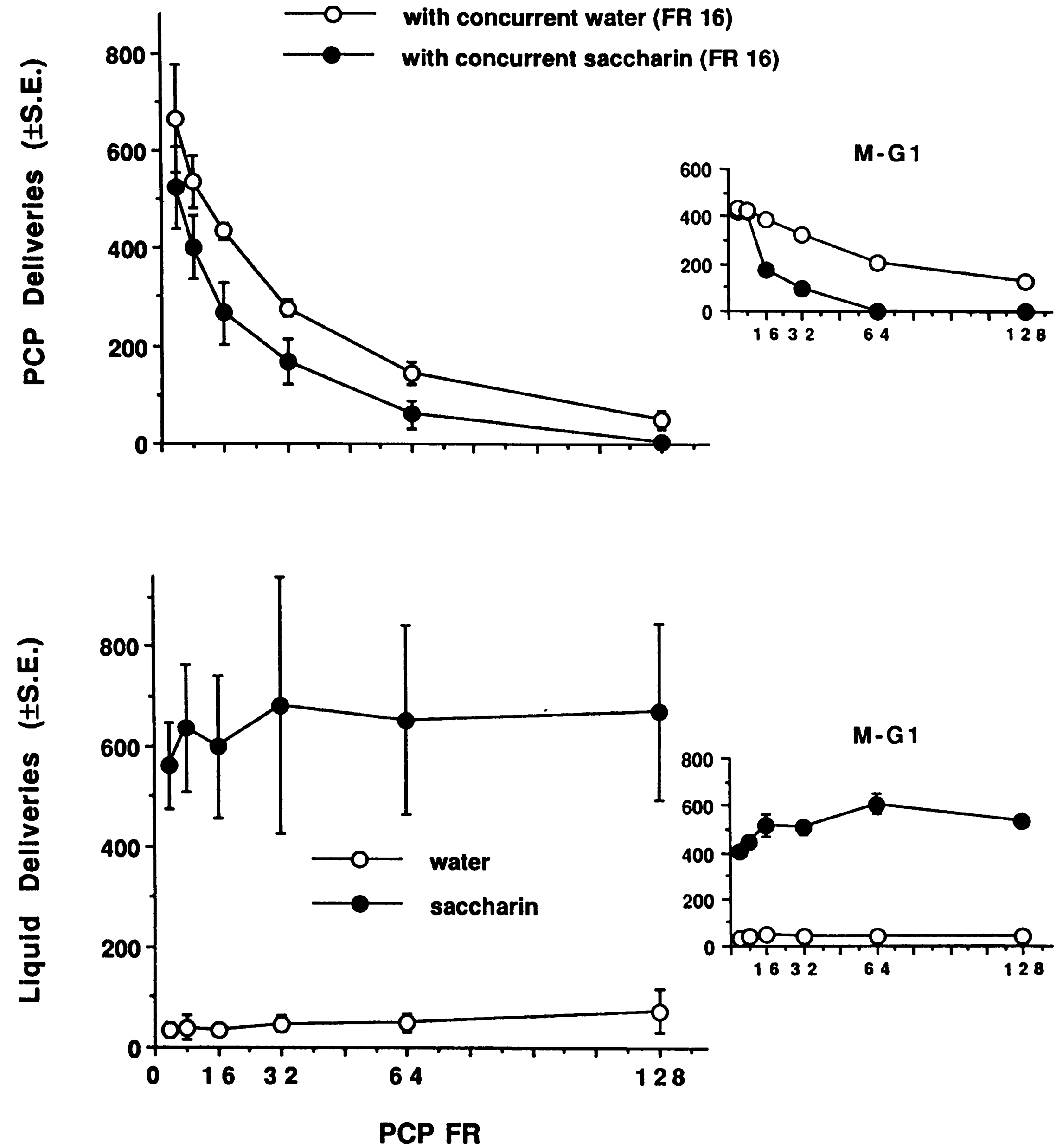

Fig. 1. Mean liquid deliveries ($\pm SE$) are presented as a function of the PCP FR value. The upper frames show the number of PCP deliveries when saccharin (filled circles) or water (open circles) was concurrently available. These are the results of Condition 1, in which the PCP FR was varied and the saccharin or water FR remained fixed at 16. The lower frames show the number of saccharin (filled circles) and water (open circles) deliveries while these substances were concurrently available with PCP. Inserts show individual data for M-G1. Each point represents a mean of 5 days of stable behavior for 6 monkeys. Standard errors were calculated each day for 6 monkeys and were averaged over 5 days.

and the FR for saccharin or water remained fixed at 16. PCP deliveries markedly decreased as the FR increased, and this effect was greater when saccharin was concurrently available compared with the condition when water was available. The concurrent saccharin or water deliveries did not substantially change as the FR for PCP changed. The PCP and saccharin

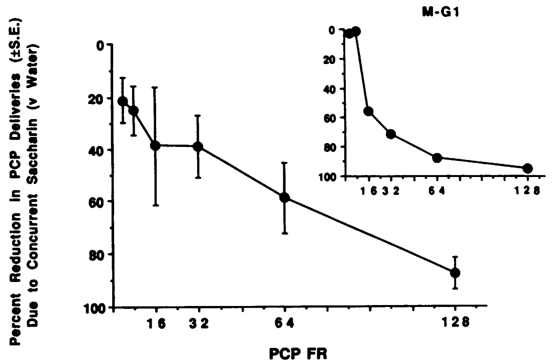

Fig. 2. Mean ($\pm SE$) percentage reductions in PCP intake when saccharin versus water was concurrently available are presented for the range of FR values for PCP. Percentage reductions were calculated as follows: (number of PCP deliveries with water concurrently present − number of PCP deliveries with saccharin concurrently available) / number of PCP deliveries with water present × 100. These are the results of Condition 1, in which the FR for PCP was varied and the saccharin or water FR remained fixed at 16. The insert shows individual data for M-G1. Each point refers to a mean of 5 days of stable behavior for 6 monkeys averaged over 5 days.

Table 2

Slope of demand curves (liquid deliveries × FR value).

	Condition 1	Condition 2	Condition 3
PCP (0.25 mg/mL)	−3.6	—[a]	−3.0
with saccharin	—	−8.5	−7.8
PCP (0.25 mg/mL)	−4.4	—	−4.7
with water			
PCP (0.125 mg/mL)	−3.6		−3.2
with saccharin	—		−8.8
PCP (0.125 mg/mL)	−6.6		−6.3
with water			

[a] FR did not vary and demand could not be obtained.

deliveries were substantially higher than those for water, indicating that these substances were effectively functioning as reinforcers. When the FRs for PCP and saccharin were the same under the concurrent FR 16 conditions, saccharin deliveries were higher than those for PCP. Intersubject variability was high at the lower FRs. However, each monkey consistently reduced its PCP intake when saccharin instead of water was concurrently present. The inserts in Figure 1 show individual data for M-G1. The individual data from the other 5 monkeys showed a similar pattern. The data in Figure 1 can also be interpreted as a demand curve in which consumption (PCP deliveries) is plotted as a function of price (FR for PCP). When these functions were plotted on log log scales (not shown), the slopes of the demand curves were −4.4 and −3.6 when concurrent water or saccharin was available, respectively (see Table 2). These curves are considered to be elastic. Retest values obtained at FR 16 are not plotted, because they were nearly identical to the initial condition and, therefore, indicate a lack of time-dependent or order effects.

Figure 2 summarizes the effect of concurrent saccharin and water on PCP intake. The percentage reduction in PCP intake when concurrent saccharin was present (compared to when water was present) is plotted for each of the six FR values tested. This was calculated as follows: (number of PCP deliveries with water concurrently present − number of PCP deliveries with saccharin concurrently available)/number of PCP deliveries with water present × 100. As the FR for PCP or price increased, there was an increase in the percentage reduction in PCP deliveries due to the availability of concurrent saccharin. The decreases in PCP intake due to the presence of concurrent saccharin ranged from approximately 20% to 90% of the concurrent water condition. Data for individual monkeys, as shown in the insert for M-G1, showed a similar increase in the effectiveness of saccharin at reducing PCP intake as the FR for PCP increased.(Additional data for M-A1 are shown in the insert in Figure 8, and they concur with these results.)

Figure 3 summarizes the condition in which the FR or price of the substance concurrently available with PCP (saccharin or water) was changed, but the FR for PCP was held constant at 16. Decreases in the number of PCP deliveries were reduced by the presence of concurrent saccharin only at the lower FRs (4, 8, or 16), and there was no difference in PCP deliveries when the FR for the saccharin was 32, 64, or 128. The lower frame illustrates the lack of effect of the concurrent saccharin, as saccharin intake diminished rapidly as the FR increased. When these data were plotted on a log log scale, the slope of the saccharin function was −8.5, which is considered to be elastic (see Table 2). The decline in saccharin-maintained responding as the FR increased was similar to that shown for PCP deliveries (Figure 1, upper frame). Water deliveries were

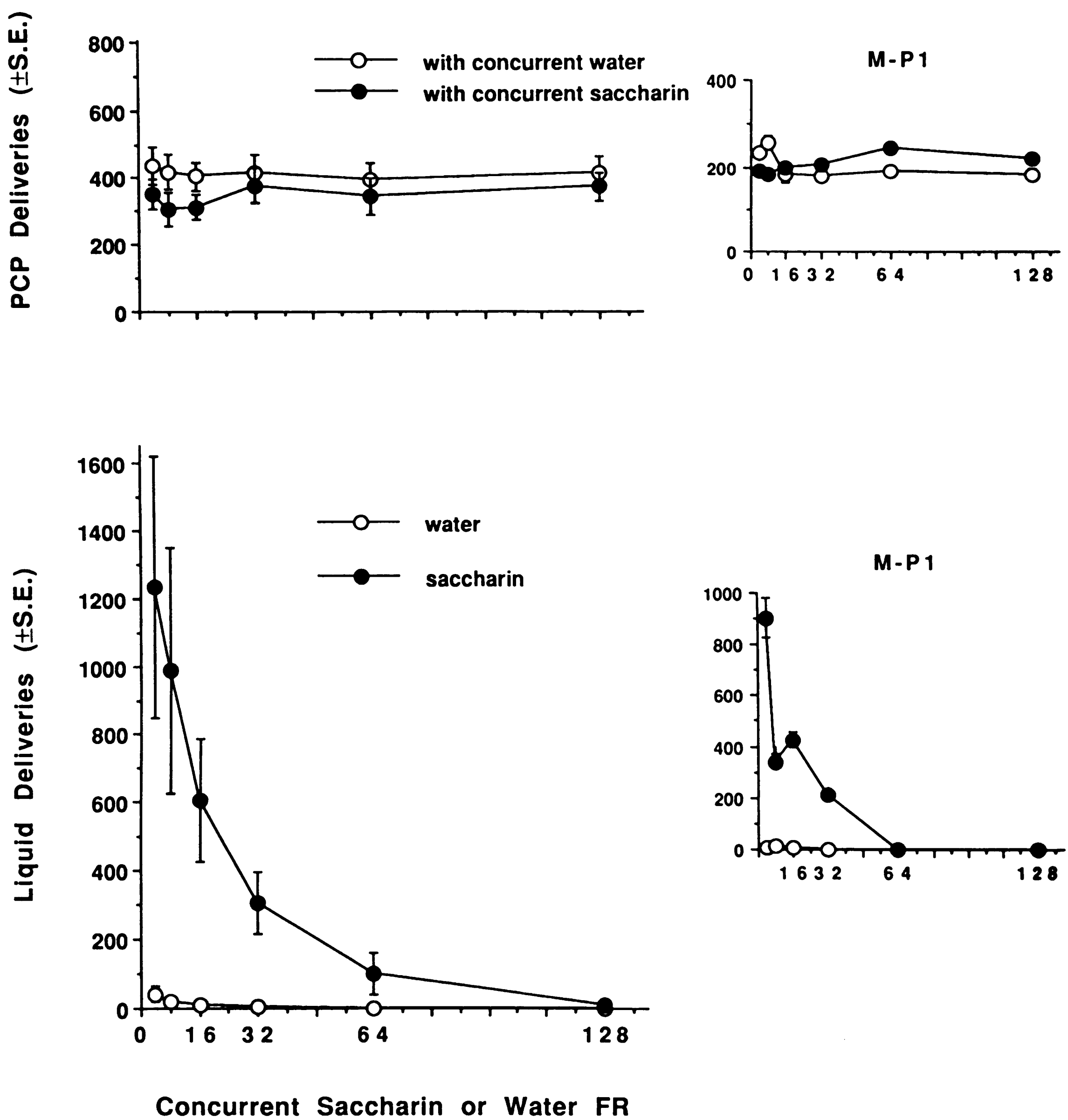

Fig. 3. Mean liquid deliveries (±*SE*) are presented as function of FR value for saccharin or water. The upper frames show the number of PCP deliveries when saccharin (filled circles) or water (open circles) was concurrently available. These are the results of Condition 2, in which PCP FR remained fixed at 16 and the FR value of the concurrent saccharin or water was varied. The lower frames show the number of saccharin (filled circles) and water (open circles) deliveries while these substances were concurrently available with PCP. Inserts show individual data for M-P1. Each point represents a mean of 5 days of stable behavior for 6 monkeys. Standard errors were calculated each day for 6 monkeys and were averaged over 5 days.

low as in the first condition (Figure 1); however, water-maintained responding decreased to almost no deliveries as the FR was increased. There was essentially no demand for water. Water deliveries were often near zero on many days for most monkeys. When water drinking did occur, it was later in the session after the monkeys showed some signs of PCP intoxication. Similar patterns have been presented previously (Carroll & Stotz, 1984). The

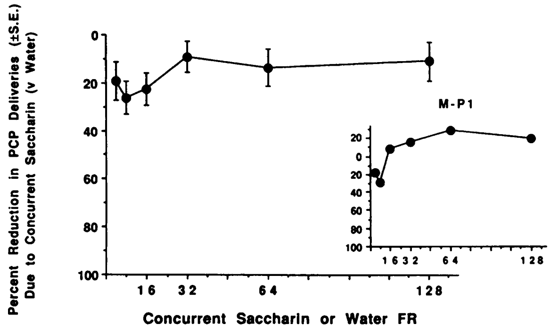

Fig. 4. Mean ($\pm SE$) percentage reductions in PCP intake when saccharin versus water was concurrently available are presented for the range of FR values. Calculations for percentage reduction are described in the legend for Figure 2. These are the results of Condition 2, in which the FR for PCP remained fixed at 16 and the FR for saccharin or water was varied. The insert shows indiviual data for M-P1. Each point refers to a mean of 5 days of stable behavior for 6 monkeys. Standard errors were calculated each day for 6 monkeys and were averaged over 5 days.

intersubject variability under these conditions was high at the lower FR values; however, all 6 monkeys consistently decreased their PCP deliveries at the three lower FR values. Also, as noted for the first condition when the FRs were 16 for both liquids, the saccharin deliveries were considerably higher than the PCP deliveries. Data from individual monkeys (e.g., M-P1) showed a similar pattern to that represented by the mean.

Figure 4 shows the mean percentage reduction in PCP deliveries due to concurrent saccharin (vs. water) when the FR for PCP was fixed at 16 and the FR of the concurrently available liquid was varied. (The calculation of this percentage reduction is described for Figure 2.) As noted in Figure 3, there were substantial reductions in PCP intake only when saccharin or water was available at the three lowest FRs (4, 8, or 16). At these FRs, the percentage reductions ranged from approximately 20% to 30% of the concurrent water condition. At the higher FR values, there was little suppression in PCP intake due to the concurrent availability of saccharin, reflecting the fact that little saccharin was consumed. Data from M-P1 reflect these patterns represented by the means.

Figure 5 shows the effect of increasing the FR for PCP and concurrent saccharin or water simultaneously. The reduction in PCP intake due to the increase in FR value was nearly identical to that shown in Figure 1 when water was concurrently available. There was less of a reduction in PCP intake due to concurrent saccharin when the FR for saccharin also increased (Figure 5) compared to when the FR for saccharin was fixed at 16 (Figure 1). However, the PCP deliveries were consistently lower when saccharin was concurrently available than when water was present. When the demand curves were plotted on log log scales (not shown), the slopes of the PCP curves were -4.7 and -3.0 when water or saccharin was concurrently available, respectively (see Table 2). These are considered to be elastic. There was essentially no demand for water.

The lower frame shows the effect of changing the FR on saccharin and water deliveries. The saccharin and water functions were very similar to those reported in Figure 3; thus, the changes in FR for PCP had little effect on concurrent saccharin or water intake. The saccharin deliveries decreased markedly as the FR increased (Figure 5). When plotted on log log coordinates the slope of the saccharin curve was -7.8, indicating elasticity (see Table 2). Water deliveries started low at FR 4, and decreased to near zero. As found in the previous conditions, there was greater intersubject variability at the lower FRs; however, individual subject data, as illustrated by M-G2 in the inserts, showed a similar pattern across subjects. When both PCP and saccharin were available under the concurrent FR 16 schedules, saccharin-maintained responding was nearly twice that maintained by PCP.

Figure 6 compares the percentage reductions in PCP deliveries when saccharin was concurrently available compared to water. (The calculation of the percentage reductions is described for Figure 2.) The reductions ranged from 20% to 40% of the concurrent water condition; however, there was no systematic trend as a function of FR value (i.e., saccharin availability resulted in a fixed proportional decrease). Individual subject data, as illustrated by those of M-G2 (Figure 6), also showed no specific trend in the relationship between FR value and percentage reduction in PCP deliveries due to saccharin. (Additional data for M-A1 are shown in the insert for the left frame of Figure 8, and they concur with these findings.)

The results of decreasing the PCP concentration to 0.125 mg/mL and retesting Con-

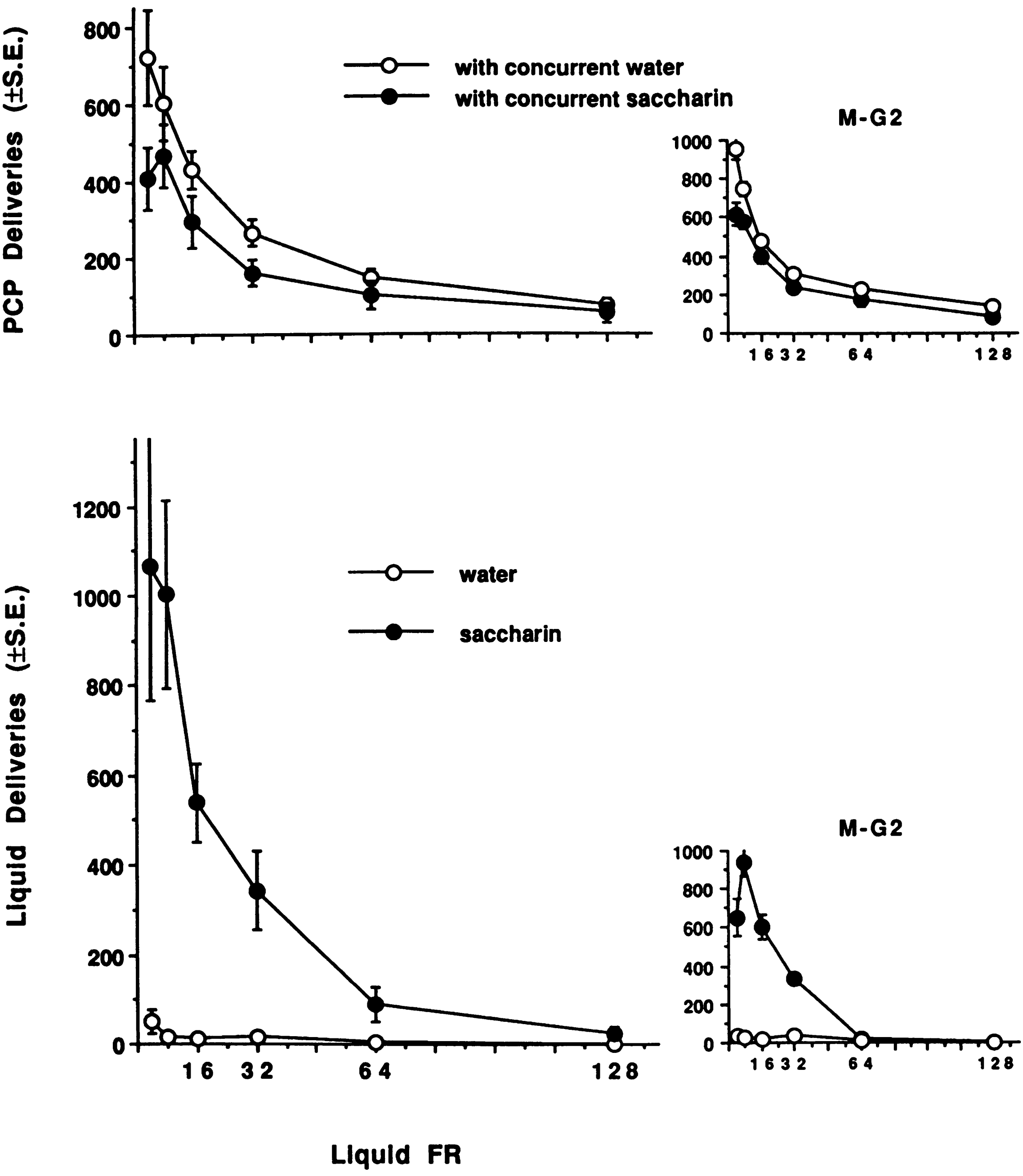

Fig. 5. Mean liquid deliveries (±*SE*) are presented as a function of liquid FR value. The upper frames show the number of PCP deliveries when saccharin (filled circles) or water (open circles) was concurrently available. These are the results of Condition 3, in which the PCP and concurrent saccharin or water FRs were varied simultaneously. The lower frames show the number of saccharin (filled circles) and water (open circles) deliveries while these substances were concurrently available with PCP. Inserts show individual data for M-G2. Each point represents a mean of 5 days of stable behavior for 6 monkeys. Standard errors were calculated each day for 6 monkeys and were averaged over 5 days.

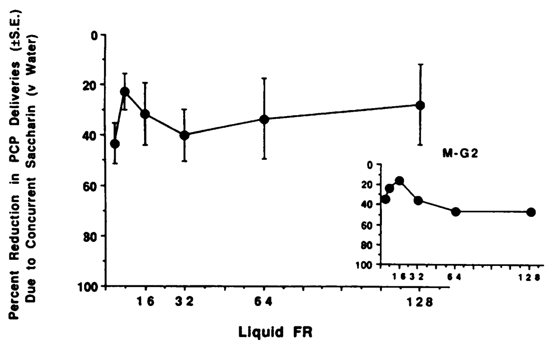

Fig. 6. Mean (±*SE*) percentage reductions in PCP intake when saccharin versus water was concurrently available are presented for the range of FR values. Calculations for percentage reduction are described in the legend for Figure 2. These are the results of Condition 3, in which the PCP and concurrent saccahrin or water FRs were varied simultaneously. The insert shows individual data for M-G2. Each point refers to a mean of 5 days of stable behavior for 6 monkeys. Standard errors were calculated each day for 6 monkeys and were averaged over 5 days.

ditions 1 and 3 (Table 1) are shown in Figure 7. The PCP deliveries in the presence of water were consistently higher at the 0.125 mg/mL PCP concentration than they were when the PCP concentration was 0.25 mg/mL (see Figure 1). However, the PCP deliveries with concurrent saccharin were nearly identical whether the PCP concentration was 0.125 (Figure 7) or 0.25 mg/mL (Figure 1). Thus, the net effect of concurrent saccharin on PCP intake was greater at the lower PCP concentration. Saccharin and water consumption was comparable to amounts reported (Figures 1 and 5) when the higher PCP concentration was available; thus, PCP concentration had little effect on saccharin-maintained responding. Individual data exemplified by M-A1 reflected the results expressed by the means.

Figure 8 summarizes the percentagè reductions in PCP intake due to the availability of concurrent saccharin (vs. water) for Conditions 1 and 3 (Table 1) comparing the higher and lower PCP concentrations. (The calculations used to obtain the percentage reductions are described for Figure 2.) The reductions in PCP intake due to concurrent saccharin were greater when the lower PCP concentration (0.125 mg/mL) was used. They ranged from 40% to 90% as the FR was increased from 4 to 128. The difference is due almost entirely to the increased PCP-reinforced responding at the lower concentration (0.125 mg/mL) in the presence of water. In Condition 1, when only the FR for PCP was changed, the effect of saccharin on PCP intake (percentage reduction) became progressively greater as the FR for PCP increased (left frame). In Condition 3, when both FRs were changed simultaneously (right frame), there was a parallel shift downward in the percentage reduction in PCP deliveries due to concurrent saccharin. At most FR values in both Conditions 1 and 3, saccharin had a greater effect on reducing PCP deliveries when the PCP concentration was lower (0.125 mg/mL).

Note that although price (FR values) remained the same when the two PCP concentrations were compared, the unit price (responses per milligram) increased when the concentration was reduced. For instance, at FR 16, the unit price for the higher PCP concentration (0.25 mg/mL) was 64 responses per milligram, and the unit price for the lower PCP concentration (0.125 mg/mL) was 128 responses per milligram. When plotted on log log coordinates, the slope of the PCP (0.125 mg/mL) curve in Condition 1 was −3.6 with saccharin and −6.6 with water concurrently available (see Table 2). In Condition 3, the slope of the PCP (0.125 mg/mL) curve was −3.2 with saccharin and −6.3 with water concurrently available (see Table 2). The slope for the saccharin function in Condition 3 was −8.8 (see Table 2). All of these slopes were elastic, but there was less elasticity for PCP when saccharin (vs. water) was concurrently present, and there was less elasticity for PCP than saccharin. These results agree with those obtained at the higher PCP (0.25 mg/mL) concentration (Table 2). Although there was considerable variability across monkeys at the low FRs, the data from individual animals (represented by M-A1) were similar to those shown by the group means.

In Figure 9 the data from the two concentration series (0.125 and 0.25 mg/mL) are compared in a unit-price analysis. These data represent Condition 1, in which the FR for PCP was varied and the FR for concurrent saccharin or water was fixed at 16 (upper frames), and Condition 3, in which the FRs for PCP and concurrent saccharin or water were varied simultaneously (lower frames). Consumption or intake (in milligrams) is plotted on log log coordinates as a function of unit price, or the number of responses per milligram of PCP delivered. A comparison of the two curves reveals that similar functions were

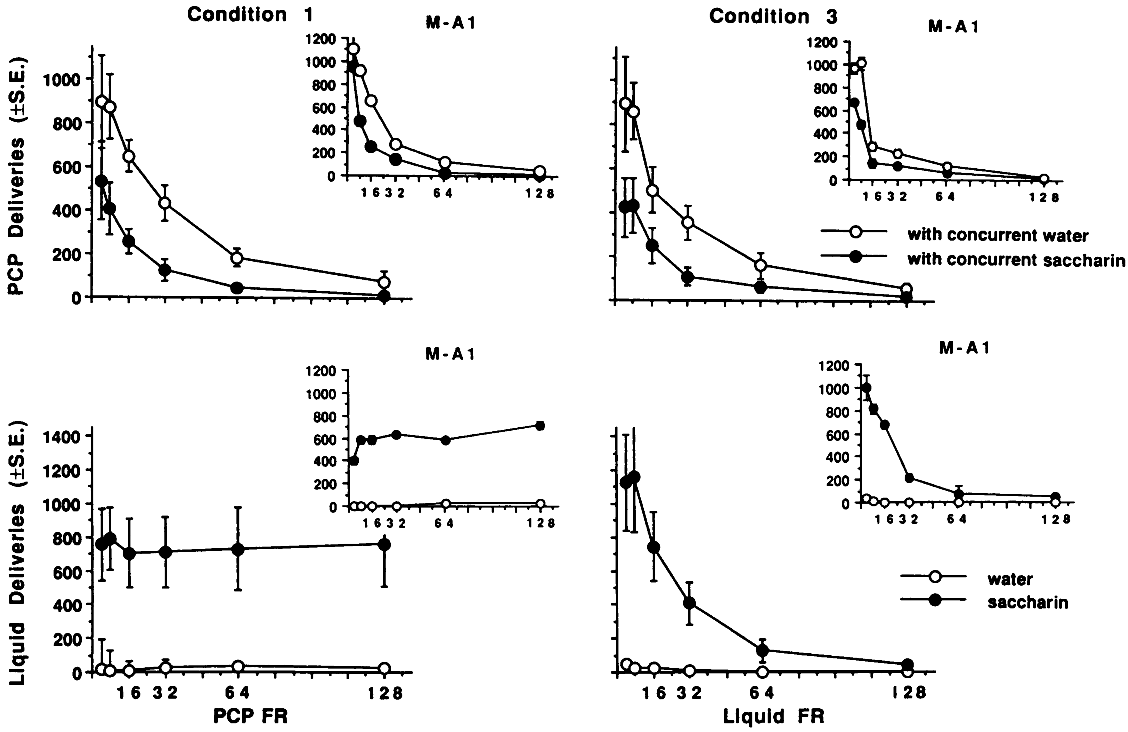

Fig. 7. Mean liquid deliveries (±*SE*) are presented as a function of the liquid FR value. The upper frames show the number of PCP deliveries when saccharin (filled circles) or water (open circles) was concurrently available. The left frames show the results of Condition 1, in which the FR for PCP was varied and the saccharin or water FR remained fixed at 16. The right frames show the results of Condition 3, in which the PCP and concurrent saccharin or water FRs were varied simultaneously. The lower frames show the number of saccharin (filled circles) and water (open circles) deliveries when these substances were concurrently available with PCP. Inserts show individual data for A1. Each point represents a mean of 5 days of stable behavior for 6 monkeys. Standard errors were calculated each day for 6 monkeys and were averaged over 5 days.

obtained regardless of drug concentration when water was the concurrently available liquid; thus, changing either the FR for PCP or the concentration were functionally equivalent. Generally, functional equivalence of FR and concentration manipulations was maintained when saccharin was concurrently available, as most of the curves were superimposed. However, the group and individual curves were lower at several unit prices when the lower PCP concentration (0.125 mg/mL) was available.

DISCUSSION

In this experiment, saccharin (0.3 wt/vol) and both concentrations of PCP (0.125 and 0.25 mg/mL) clearly functioned as reinforcers. At FR 16, for example, PCP deliveries ranged between 400 and 500, saccharin deliveries were between 500 and 600, and water deliveries (vehicle) remained below 50 across all three experimental conditions. Criteria that indicate that an orally delivered drug or substance functions as a reinforcer are that deliveries exceed those of the vehicle, usually water, and that the substance maintains characteristic patterns of intermittently reinforced behavior (Meisch & Carroll, 1987). Thus, in terms of number of liquid deliveries, the PCP and saccharin solutions were preferred to their vehicle (water), and they maintained behavior on FR schedules whereas water did not. PCP and saccharin were relatively equivalent as reinforcers.

Effects of Saccharin on PCP-Reinforced Behavior: Increasing the Cost of PCP (Condition 1)

The results of Condition 1, in which the FR for PCP was changed from 4 to 128 and the FR for concurrent saccharin or water remained fixed at 16, confirm previous results (Carroll, 1985) showing that concurrent sac-

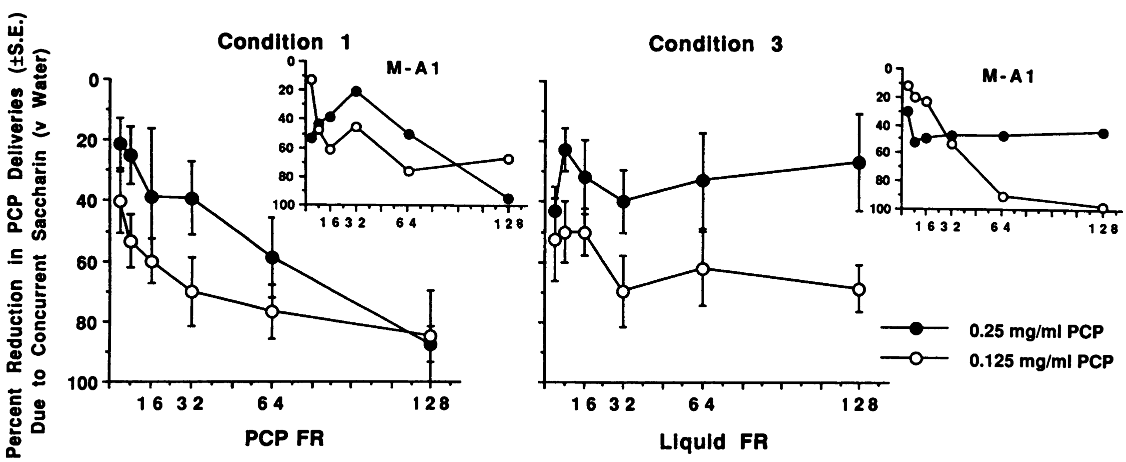

Fig. 8. Mean (±*SE*) percentage reductions in PCP intake when saccharin versus water was concurrently available are presented for the range of FR values, and the 0.125 and 0.25 mg/mL PCP concentrations are compared. Calculations for percent reductions are described in the legend for Figure 2. The left frames show the results of Condition 1, in which the FR for PCP was varied and the FR for concurrent saccharin or water remained fixed at 16. The right frames represent the results from Condition 3, in which the PCP and concurrent saccharin or water FRs were varied simultaneously. Filled circles refer to the 0.25 mg/mL PCP concentration, and open circles refer to the 0.125 mg/mL PCP concentration. Inserts show individual data for M-A1. Each point represents a mean of 5 days of stable behavior for 6 monkeys. Standard errors were calculated each day for 6 monkeys and were averaged over 5 days.

charin availability decreases PCP-reinforced responding. With both concentrations of PCP (0.125 and 0.25 mg/mL), the effect of saccharin on reducing PCP intake became greater as the FR for PCP or price of PCP increased. The amount that PCP-reinforced behavior was reduced (compared to the condition in which water was concurrently available) increased from 20% to 90% as the FR for PCP was increased from 4 to 128. Thus, the degree to which concurrently available saccharin reduced PCP-reinforced responding was dependent upon the FR for PCP.

Another factor that determined the extent to which concurrently available saccharin reduced PCP-reinforced behavior was the PCP concentration. There was a greater reduction in PCP deliveries when saccharin was concurrently present (compared to water) at almost all FR values for the 0.125 mg/mL PCP concentration compared with the 0.25 mg/mL concentration (Figure 8). In a previous study, the FR for PCP was held constant at 16 and PCP concentration was varied. Concurrent saccharin produced a greater decrease in PCP-reinforced behavior at concentrations of 0.125 mg/mL and lower. A reduced suppressant effect was found at PCP concentrations of 0.25 mg/mL and higher (Carroll, 1985). In other studies, food was manipulated as an alternative reward, and the results showed that the effectiveness of ad-lib access to food in reducing drug intake was inversely related to the drug dose (Takahashi, Singer, & Oei, 1978) or concentration (Carroll & Stotz, 1984). In fact, at high concentrations (0.5 and 1 mg/mL), concurrent ad-lib food, saccharin, or ethanol had almost no effect (Carroll, Stitzer, Strain, & Meisch, 1990) on PCP-reinforced behavior.

Both of these variables, FR for PCP and PCP concentration, are constituents of unit price (responses per milligram of drug consumed). The analysis of both PCP concentration and cost (FR) in terms of unit price in the present experiment provided further evidence that the unit price determines whether drug-reinforced behavior is sensitive to a competing reinforcer. The results were similar when either constituent of unit price (response requirement or drug concentration) was varied with concurrent water available (Figure 9). However, when saccharin was concurrently available, the demand curves were not as closely superimposed. For several unit prices the demand for PCP was lower at the 0.125 mg/mL PCP concentration than it was at the higher concentration (0.25 mg/mL). There is a narrow concentration-response function for PCP as an orally delivered reinforcer. The lower concentration used in the present experiment

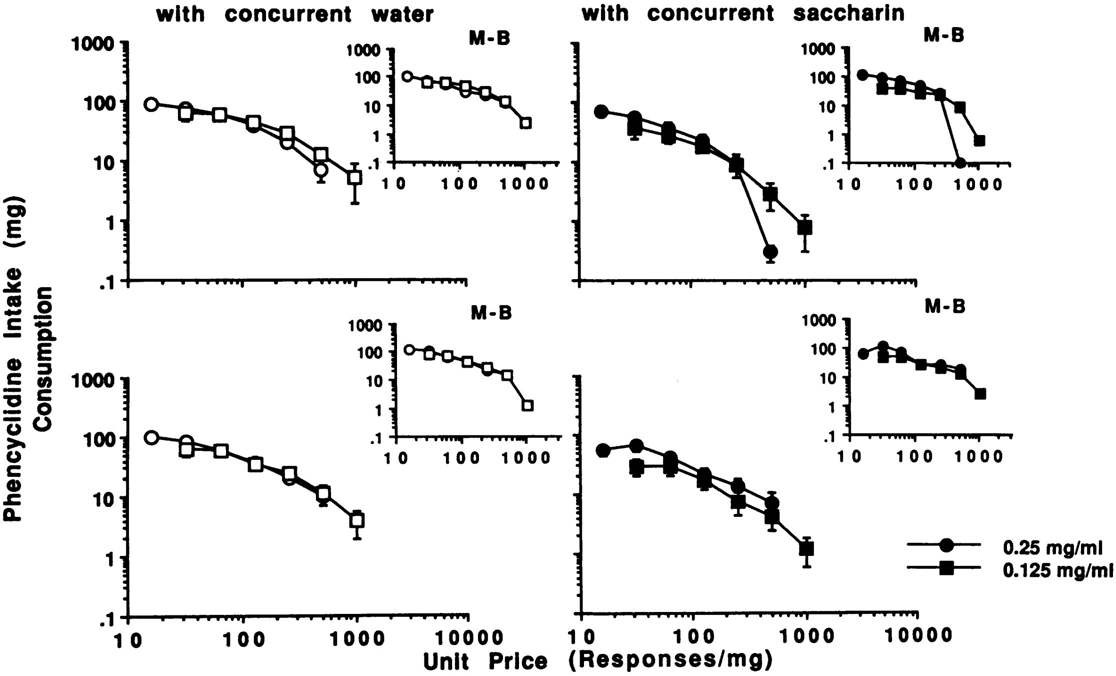

Fig. 9. Demand curves are presented for the two concentrations of PCP tested (0.125 and 0.25 mg/mL). Condition 1, in which only the FR for PCP was varied, and Condition 3, in which the FRs for both saccharin and PCP were varied, are represented in the upper and lower frames, respectively. Consumption or PCP intake is plotted as a function of unit price, which is defined as the number of responses emitted per milligram of PCP consumed. Thus, the higher the FR value, the greater the unit price. Filled symbols represent demand curves for PCP when saccharin was concurrently available, and open symbols refer to demand curves for PCP when water was concurrently available. Squares refer to the lower PCP concentration (0.125 mg/mL) and circles represent the higher PCP concentration (0.25 mg/mL). Inserts show individual data for M-B. Each point represents a mean of 5 days of stable behavior for 6 monkeys. Standard errors were calculated each day for 6 monkeys and were averaged over 5 days.

(0.125 mg/mL) is near the threshold for demonstrating a reinforcing effect (consumption in excess of vehicle). Further work will be needed to determine the usefulness of a unit-price analysis at the outer ranges of the concentration-response function.

Effects of Saccharin on PCP-Reinforced Behavior: Increasing the Cost of Saccharin (Condition 2)

The results of Condition 2, in which the FR for PCP remained fixed at 16 and the concurrent saccharin or water FR was varied, indicated that saccharin reduces PCP intake only when its cost is relatively low and a substantial quantity of the substance is self-administered. For instance, at the three lowest FRs (4, 8, and 16), large amounts of saccharin were consumed (e.g., 600 to 1,200 deliveries), and the reduction in PCP intake ranged from 20% to 30% (compared to when water was concurrently available), as it had when saccharin access was contingent upon an FR 16 schedule in Condition 1. However, as the cost of saccharin increased with FRs of 32, 64, and 128, intake decreased from 300 to nearly zero deliveries, and there was only a minimal reduction (e.g., 10%) in PCP deliveries. Thus, the effectiveness of saccharin on lowering PCP intake depended on the unit price of saccharin being relatively low. Another indication of this inverse relationship is found in a comparison of Conditions 1 and 3. The saccharin intake at FR 4 (Condition 3) was considerably higher than it was at FR 16 (Condition 1), and the corresponding PCP intake was lower (44% vs. 20%) when the greater amount of saccharin was consumed (in Condition 3 vs. 1, respectively). Saccharin intakes were equally as high at FR 8, but the inverse relationship with PCP intake was not upheld. A similar effect was achieved in the earlier study (Carroll, 1985) by lowering the other constituent of unit price, concentration. When the saccharin concentration was reduced to 0.003 (wt/vol), there were only minimal reductions in PCP self-administration, and they occurred only at the low PCP concentrations.

Effects of Saccharin on PCP-Reinforced Behavior: Increasing the Cost of Both Saccharin and PCP (Condition 3)

In Condition 3, the FRs for both PCP and concurrent saccharin or water were changed to reflect a general environmental constraint, compared to the more specific constraints of changing either PCP or saccharin price alone in Conditions 1 and 2, respectively. The purpose of varying the cost of the PCP and saccharin simultaneously was to determine whether saccharin was more effective at reducing PCP intake when both substances were relatively expensive or relatively inexpensive, and to compare the two substances in terms of their sensitivity to price increases. The results of Conditions 1 and 2 indicated that the optimal situation for reducing drug intake is when the drug is relatively expensive and when the alternative reinforcer is relatively inexpensive. The results of Condition 3 showed a relatively constant decrease in PCP-reinforced behavior across all FR values tested; thus, increased cost did not differentially affect the drug and nondrug reinforcer. The decreases (compared to concurrent water) ranged from 20% to 40%.

The Effect of PCP on Saccharin-Reinforced Behavior

A comparison of the results of Conditions 2 and 3 provides a situation in which price of PCP deliveries was either fixed at 16 or varied, and the FR for saccharin was allowed to vary. Although PCP intake was substantially reduced as the FR increased, the resulting demand curves for saccharin (Figures 3 and 5, lower frames) were nearly identical, indicating that the demand for PCP (Figures 3 and 5, upper frames) had little effect on saccharin intake. A comparison of the two PCP concentrations in Conditions 1 and 3 shows that more PCP was consumed (mg/kg) when the higher concentration (0.25 mg/mL) was available. This difference was not related to differences in the saccharin functions. Consumption of saccharin was a function of FR value, and the number of saccharin deliveries did not seem to be altered by differing numbers of PCP deliveries. In behavioral economic terms, demand for a commodity is defined as the change in consumption as a function of change in price. When an increase in the cost for one commodity (and resulting decrease in consumption) results in an increase in consumption of another commodity, the relationship is called "substitution." The present data indicate that PCP did not function as an effective substitute for saccharin, and saccharin did not function as an effective substitute for PCP. The relationship between PCP and saccharin is considered to be largely independent.

The application of economic principles provides a means of understanding and quantifying interactions between drug and nondrug reinforcers. Two economic concepts were particularly useful in the present study; unit price and elasticity of demand (Samuelson & Nordhaus, 1985). The unit-price analysis presented in Figure 9 showed that drug concentration and FR schedule requirement have a functional equivalence, although the unit-price functions for the two PCP concentrations were not completely superimposed when saccharin was concurrently available. These two variables have often previously been considered separately as variables that control drug intake (Carroll, 1987a; Lemaire & Meisch, 1984), and their interaction has been carefully analyzed (e.g., Lemaire & Meisch, 1984, 1985). Bickel et al. (1990) reanalyzed data from many previous experiments (e.g., Lemaire & Meisch, 1984, 1985) and demonstrated a functional equivalence between response requirement and dose of drug per administration across a wide range of studies. Their log log plots of the demand curves consistently resulted in positively decelerating functions, as shown in the present experiment (Figure 9). The concept of unit price gains validity by such repeated demonstrations of similar functional relationships between consumption and the constituents of unit price.

The second concept, elasticity of demand, is a means of evaluating reinforcing efficacy along a dimension that is different than response rate, choice, or performance output (e.g., break point on a progressive-ratio schedule). Elasticity is defined as a performance change as a function of change in price. When consumption of a specific substance does not substantially decrease as the price of that substance increases, the demand for the substance is termed inelastic. In this case, the demand curve has a slope of −1 or greater. Economists describe such an item as essential or important to the consumer because consumption was defended even at high costs. In contrast, if consumption of a commodity decreased markedly as price increased, the demand is said to be elastic. The commodity is considered to be less important. The slope of such a demand curve is less than −1. The demand for both PCP and saccharin in the present experiment was elastic. The demand for saccharin was more elastic than the demand for PCP. When saccharin (vs. water) was concurrently available with 0.25 mg/mL PCP, the slopes changed only from −3.6 to −4.4 and from −3 to −4.7 in Conditions 1 and 3, respectively. When saccharin (vs. water) was concurrently available with the lower PCP concentration (0.125 mg/mL), the slopes changed from −3.6 to −6.6 and from −3.2 to −6.3 in Conditions 1 and 3, respectively. Thus, saccharin decreased PCP-reinforced responding, but the resulting demand function for PCP became less elastic when concurrent saccharin (compared with water) was available. The evaluation of elasticity of demand provides more information about the reinforcing effects of two qualitatively different reinforcers than rate, choice, or breakpoint measures. For instance, the number of liquid deliveries indicated that PCP and saccharin had similar reinforcing effects; however, the elasticity of demand for saccharin was greater than that for PCP. Furthermore, the comparison of demand curves indicated that concurrent saccharin reduced the intensity of demand for PCP, but concurrent PCP did not reduce the intensity of demand for saccharin. Intensity of demand is indicated by a parallel shift up or down in the demand curve. It would also be useful to evaluate the effect of other reinforcers on the intensity of demand for drugs.

In summary, the present experiment demonstrated that the availability of an alternative nondrug reinforcer results in a reduction in drug-reinforced behavior by up to 90% of the baseline condition depending on the economic parameters of the drug and nondrug reinforcers. The optimal conditions for reducing drug intake occur when the cost of the drug is high and the price of the alternative reinforcer is low. The unit price of the drug was altered both by changing the response requirement (FR value) and by changing the drug concentration. The results indicate that these constituent variables are functionally equivalent, and that unit price of the drug (responses per milligram) is an important determinant of the effects of the alternative reinforcer.

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